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Art. XXVII.—*The Magnetic Properties of Stalloy.*

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(With Plates LXII.-LXV.).

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(Communicated by Professor T. R. Lyle).

In the following paper are given the results of an investigation into the magnetic properties of the iron alloy called "Stalloy." Particular attention has been given to "Stalloy" by many investigators on account of the claims made by its inventor (Hadfield) with regard to its magnetic properties. The special feature of this alloy is its high specific electric resistance and high permeability. The specific resistance being about four times that of the best transformer iron, the eddy-current loss for a given thickness of sheet would be greatly reduced, so that lamination need not be carried out to anything like the extent necessary with ordinary iron, and the question of insulation of laminae becomes less troublesome. It is more expensive than ordinary iron, but the increased expense is compensated by a reduction in size of the transformers etc., constructed of it, an increase in output, and greatly improved efficiency.

The special chemical feature of "Stalloy" is that it contains about 3.4 per cent. Silicon. The value of this alloy is emphasised in a paper by Epstein[1], where several tests of its properties are given.

Several investigations have been made by other experimenters by direct current methods, which agree fairly well together.

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[1] Epstein. J.I.E.E., vol. xxxvi., 1907. Professor Turner gives the analysis as follows: Carbon .03, Silicon 3.4, Sulphur .04, Phosphorus .01, Manganese .32, Iron 96.20 per cent.

The most interesting of these are given by Wilson and others[1], Watson,[2] and the manufacturers, Sankey and Sons.[3]

Some interesting experiments on an alloy very closely allied to "Stalloy" are given by Barrett, Brown, and Hadfield[4], and by Baker.[5]

The object of the present research was to investigate the magnetic properties of "Stalloy," not only with direct current, but also with alternating currents of varying frequencies. quencies.

The experiments have been divided into three divisions:—

(1) Statical tests.

(2) Effect of variation of frequency on magnetic hysteresis.

(3) Effect of annealing upon each of the above.

The usual statical experiments were made for inductions extending up to about 14,000. From these results were calculated the hysteresis losses and Steinmetz coefficients using as exponent in the usual formula the value 1.6 which was found to be approximately correct for this substance. The determination of these coefficients is important as from their values we are able to separate the hysteresis from the total loss in each of the alternating experiments.

The tests were made upon two rings as nearly alike as possible, one annealed, the other unannealed.

The alternate current experiments were divided into three series, of periods .07, .035, .02 respectively. In each of these the period and wave form of the magnetizing current were kept as nearly as possible constant as the induction density increased. The expressions for the amplitude and phase both of H and B are given in the tables which follow.

From these expressions, for each pair of associated waves of H and B was calculated the total loss per c.c. per cycle (I).

This was found to follow fairly well a formula proposed by Lyle[3] for total loss in iron, namely:—

$$I = (\alpha + \beta n)\mathfrak{B}^{x}$$

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[1] Wilson, Winson and O'Dell. Proc. Roy. Soc. Lond., 1908, vol. lxxx,

[2] Watson. Electrician, vol. lx., p. 4.

[3] Article "Stalloy." Electrician, vol. lviii., p. 692.

[4] Barrett, Brown and Handfield. J.I.E.E., 1902.

[5] Baker. J.I.E.E., December, 1904.

where α, β and r are constants for the material, n the frequency and $\mathfrak{B}$ is the "effective induction," a quantity of great importance in the calculation of the eddy current loss (E), as will be explained later.

The method employed was similar to that described by Professor Lyle[1]. By means of his wave-tracer[2] the wave forms of the magnetizing current and the resultant magnetic flux pulsating in the iron can be accurately determined. The full wave being obtained, fifteen ordinates per half wave were taken, from which, without plotting, the first, third and fifth harmonics composing the waves can be calculated. Two methods of harmonic analysis were used (1) for approximately sinusoidal waves, that devised by Lyle[3], (2) for waves into which harmonics higher than the fifth entered considerably, that of S. P. Thompson[4].

The wave forms having been analysed, the results were reduced to absolute measure by the application of proper factors[4]. The magnetizing force and induction were thereby obtained in the form—

$$H = H_1[\sin\omega t + h_3\sin 3(\omega t - \phi_3) + h_5\sin 5(\omega t - \phi_5) + \ldots\ldots\ldots\ldots]$$
$$B = B_1[\sin(\omega t - \theta) + b_3\sin 3(\omega t - \theta_3) + b_5\sin 5(\omega t - \theta_5) + \ldots\ldots\ldots]$$

In general, harmonics higher than the fifth were neglected and are not given in the tables. In calculating the total losses, however, these upper harmonics were included.

From these equations the value of the total loss per c.c. per cycle—

$$I = \frac{1}{4\pi}\int H\,dB$$
$$= \frac{H_1B_1}{4}[\sin\theta + 3h_3b_3\sin 3(\theta_3 - \phi_3) + 5h_5b_5\sin 5(\theta_5 - \phi_5)]$$

is determined.

The amount of eddy-current loss per c.c. per cycle (E) was calculated from the approximate formula given by Searle and Bedford[5].

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[1] T. R. Lyle. Phil. Mag., 1905, vol. ix.

[2] T. R. Lyle. Phil. Mag., 1903, vol. vi.

[3] T. R. Lyle. Phil. Mag., 1906, vol. xl., also Proc. Roy. Soc. Victoria, vol. xvii.

[4] S. P. Thompson. Electrician, 1905.

[5] Searle and Bedford. Phil. Trans., 1902, App.

$$\frac{dX}{dt} = \frac{x^2}{12\rho}\left(\frac{db}{dt}\right)^2$$

Where X is the space average of eddy-current loss.

x the thickness,

ρ the specific resistance,

μ the permeability being assumed constant.

From this the eddy-current loss per c.c. per cycle may be reduced to the form[5].

$$E = \frac{\pi^2 x^2}{6\rho T}\mathfrak{B}^2$$

$$\text{where } \mathfrak{B} = B_1\left[1 + 9b_3{}^2 + 25b_5{}^2 + \ldots\ldots\right]^{\frac{1}{2}}$$

$$= \frac{\sqrt{2}}{\omega}\text{R.M.S.}\left(\frac{dB}{dt}\right).$$

The statical hysteresis (U) was determined by Ewing and Klaasen's ballistic method, and from the results the Steinmetz coefficient σ obtained was plotted against the maximum induction by the use of the formula—

$$U = \sigma B^{1.6}_{\text{Max.}}$$

In order to determine the value of U for alternating currents, it was assumed that it was equal to that obtained by the statical method for maximum induction equal to the maximum value (B_0) of B. From the above mentioned graph and formula U has been calculated for all inductions.

Having obtained all these quantities, the values of I-U-E, called by Fleming the 'kinetic hysteresis,' were calculated. These as well as I, U, E, have been given for each experiment.

The rings were prepared from the same sheet and were made as nearly alike as possible. A thin sheet of waxed paper separated each pair of discs and the wire used in the winding was taken from the same coil. After the laminae were well cleaned the mean thickness was determined by the specific gravity method.

The specific resistance was determined by the "drop of potential" method against a standard .1 ohm by means of a Wolff's potentiometer. Experiments were made on two samples, one of length about 80 cms. cut from the sheet, and another from a thin annulus cut from one of the actual rings used. The results differed by less than .1 per cent and agreed fairly well with the results of other experimenters.

The details of the coils are:—

	Annealed.	Unannealed.
No. of laminae	6	6
Internal diameter	6.927 cms.	6.927 cms.
External ,,	9.549 cms.	9.557 cms.
Mean thickness (x)	.0757 cm.	.0739 cm.
Area of cross section	.5953 sq cm.	.5830 sq. cm.
Length of magnetic circuit	25.87 cms.	25.90 cms.
Primary turns	135	135
Secondary turns	10 or 50	10 or 50
Specific resistance at 19° C	50320	50440
Specific gravity at 19° C	7.58	7.582

The reduction factor of the galvanometer used in the secondary circuit was obtained by passing the current from a cadmium cell through a megohm and the galvanometer in series.

All the resistances used were carefully tested during the course of the experiments, as were also the two standard M coils which were used to determine the absolute value of the magnetizing force.

The symbols used in the accompanying tables are as follow:—

$$\mathrm{T} = \text{period} = 2\pi/\omega = \cdot 07,\ \cdot 035,\ \cdot 02 \text{ approx.}$$

$$\mathrm{H} = \mathrm{H}_1[\sin\omega t + h_3 \sin 3(\omega t - \phi_3) + h_5 \sin 5(\omega t - \phi_5) + \dots\dots]$$

$$\mathrm{B} = \mathrm{B}_1[\sin(\omega t - \theta) + b_3 \sin 3(\omega t - \theta - \psi_3) + b_5 \sin 5(\omega t - \theta - \psi_5) + \dots]$$

$$\mu_0 = \mathrm{B}_1/\mathrm{H}_1 \quad \mu = \mathrm{B}_0/\mathrm{H}_0.$$

$$\mathrm{U} = \sigma \mathrm{B}_0^{1.6} \quad \mathfrak{B} = \frac{\sqrt{2}}{\omega}\mathrm{R.M.S.}\left(\frac{d\mathrm{B}}{dt}\right)$$

I = Total loss per c.c. per cycle.
U = Statical hysteresis loss per cycle.
E = Eddy current loss per cycle.
I—U—E = Kinetic hysteresis per cycle.

In Tables I., II., III., are given the analytical results reduced from the series of experiments on the annealed ring, while

Table I. Annealed Stalloy Speed ·072 (q.p)

No	T	H_1	$-h_3$	ϕ_3	h_5	ϕ_5	B_1	θ	b_3	ψ_3	b_5	ψ_5	μ_0	B_{max}	H_{max}	μ	$\mathfrak{B}$	I	U	E	I-U-E
1	·0727	643	·0337	5°01	0078	21°17	1047	23°37	091	24·7	023	29°23	1628	1029	·655	1571	1091	65 3	69 0	3 1	–
2	0730	·915	0389	2 91	0027	35 47	2574	34 2	·133	16 2	042	21 13	2812	2426	·936	2590	2823	326 0	298 0	20·4	7 6
3	0732	1·334	0364	7·25	·0025	26 42	5338	37 14	176	9 85	·0552	12 81	3999	4857	1·379	3521	6211	1047	902·2	96 3	48·5
4	0730	1·566	0363	8·63	0073	33 90	6487	35 66	184	8 53	·0612	1039	4141	5771	1·611	3529	7674	1437	1204	151 0	82·0
5	0729	1 770	·0408	9 58	·0094	34 62	7275	33·99	·188	7·42	0647	9 80	4109	6422	1·848	3474	8678	1729	1437	193 2	98 8
6	0721	2638	·0671	2·91	·0123	10 09	9762	28·78	·203	5·99	·0757	7 65	3700	8468	2 780	3046	12000	2861	2312	374 1	174 9
7	·0719	4 434	0765	1 13	·0218	6 36	12053	22 85	215	4·85	·0859	6 16	2818	10330	4 682	2206	15240	4625	3257	603·7	764
8	·0722	7·988	·0798	–·32	0398	1 58	14731	16·02	220	3·16	·0945	5 07	1844	12447	8 385	1485	18980	7341	4502	933 0	1906
9	·0721	9 796	·0710	–7·8	0410	2·03	15380	14 78	·227	2·87	·0975	4 82	1597	12941	10·20	1269	20290	8594	4848	1082	2664
10	·0727	12 566	0728	–6·49	–·0400	35 30	16123	14·4	·234	2 66	·1016	4·27	1283	13421	13 17	1021	21310	10600	5158	1169	4273
11	·0736	17053	·0774	–9 84	–·0405	33 67	17094	11 74	241	2 05	·1047	3 79	968	14168	18·53	764	22910	13470	5678	1334	6478
12	·0749	29778	·0822	–12 36	–·0506	30 34	18270	10 77	·250	1 62	·1158	3·00	614	15068	31·60	453	25160	21160	6437	1580	13143

Table II Annealed Stalloy Speed 035 (qp)

No	T	H_1	$-h_3$	ϕ_3	h_5	ϕ_5	B_1	θ	b_3	ψ_3	b_5	ψ_5	μ_0	B_{max}	H_{max}	μ	$\mathfrak{B}$	I	U	E	I-U-E
1	0353	611	0293	6°·28	0057	33°95	345 9	10°02	0325	29°82	0091	41°16	566	343	622	551	348	9 1	13·7	64	—
2	0356	925	·0337	7 59	·0041	22·64	1848	32·68	1043	20 12	0278	25 12	1998	1740	956	1820	1953	227 6	173	20·0	34 6
3	·0350	1·192	·0335	11 61	0029	17 69	3817	40·30	1318	14 30	0334	18 23	3202	3436	1 229	2793	4149	723	518	91 9	113 1
4	0350	1 407	0372	12 97	·0045	17 70	5325	41 50	1495	11·90	0369	15 41	3783	4893	1 420	3446	5917	1214	915	187 3	111 7
5	0350	1 329	0371	15 76	·0069	17 45	7312	38 02	·1635	8 91	0438	12·19	3997	6396	1 890	3384	8301	2000	1429	367 7	203 3
6	·0352	2 272	0357	12 24	0079	15·69	8494	34 90	·1800	7·75	·0506	10 48	3739	7529	2 342	3210	9888	2619	1888	519 5	226 5
7	·0354	3 199	·0595	7·35	0147	14·43	10650	29 82	1880	6 16	0636	9 13	3329	9288	3 365	2762	12690	3984	2705	850·7	428
8	0355	6 078	·0702	1 38	0205	6·46	13586	20·56	2060	5 21	·0809	7 68	2235	11580	6 260	1803	16890	6533	3945	1503	1085

Table III Annealed Stalloy Speed ·020 (q.p)

No	T	H_1	$-h_3$	ϕ_3	h_5	ϕ_5	B_1	θ	b_3	ψ_3	b_5	ψ_5	μ_0	B_{max}	H_{max}	μ	$\mathfrak{B}$	I	U	E	I·U·E
1	0202	639	0377	16°80	0082	19°13	939	25°67	046	33°36	0078	38°24	1471	953	660	1445	949	64·4	60 4	8 4	—
2	0205	977	0321	18·18	0066	22 79	2514	40 68	083	22 88	0132	29 54	2573	2489	994	2506	2607	396 8	312	62 1	22 7
3	0206	1 249	0340	22 56	·0071	18 91	4465	47·24	114	15 90	·0163	21 39	3575	4299	1 335	3221	4733	1005	743	203 2	58 8
4	0205	1 556	0312	22 36	0049	16 16	6019	45 15	121	12 03	0185	17 34	3870	5602	1·586	3516	6424	1632	1146	375 9	106·0
5	·0206	1·850	0318	21 30	·0017	11 99	7059	42 55	132	10 61	0189	16 56	3841	6540	1 891	3460	7619	2198	1489	532 1	176·9
6	0209	2 198	0324	20 91	0058	13 59	8071	40 16	141	9 33	0273	15 19	3671	7244	2·212	3248	8851	2800	1770	702·6	327 4
7	0211	4 423	0751	10 59	0143	22 27	12104	27 74	163	6 66	0487	10·91	2736	9846	4 66	2112	13790	5625	2995	1685	945·0
8	0217	7 768	0767	5 11	0232	31 84	14401	20 85	192	4 16	·0687	7 88	1853	12333	8 28	1492	17353	8760	4443	2598	1719

Table IV. Unannealed Stalloy. Speed ·072(q.p.)

No	T	H_1	$-h_3$	ϕ_3	h_5	ϕ_5	B_1	θ	b_3	ψ_3	b_5	ψ_5	μ_0	B_{max}	H_{max}	μ	$\mathfrak{B}$	I	U	E	I-U-E
1	·0713	5340	0303	7°87	0042	28°81	724	26°85	·0956	21°03	·0278	27°48	1357	710	·547	1296	760	42·94	31	1·5	10·4
2	0715	8175	·0319	4 10	·0035	12·57	2023	33 04	·1340	16·78	·0404	19 88	2475	1910	·843	2266	2218	222·8	204	12·3	6·5
3	0714	1 265	0303	8 43	·0040	11 30	3760	31 55	·1701	10 00	0564	12 55	2972	3388	1·296	2613	4351	604·0	531	47·5	25·5
4	0722	1 467	0281	9 11	·0028	12 50	4425	30 66	1692	8 39	·0577	10 64	3016	3591	1 496	2640	5128	815·2	663	65·2	87 0
5	0714	1 656	0318	7·47	·0010	8 80	5041	29 38	1742	8·03	0626	9 32	3044	4477	1696	2635	5902	989·6	808	87·4	94 2
6	0713	4·218	0488	1 46	-·0154	9 85	9166	21 12	·1931	4 18	·0769	5·82	2173	8080	4·345	1860	11180	3175	2221	314·2	639 8
7	0709	8·546	- 0533	54 90	-·0228	2 37	12328	13 22	·1924	3·36	·0786	4·05	1442	10613	8·845	1196	15030	5379	3480	570·7	1328
8	·0729	10 40	- 0516	55 08	- 0236	0 02	13294	11 56	·2047	2·47	0825	3·93	1278	11177	10·76	1007	16533	6337	3942	671 0	1724
9	0729	17 71	-·0524	51 10	- 0279	-1 48	15069	8 11	·2222	2·36	·0838	3·82	850·8	12827	18·12	709	19178	8235	5063	903 0	2195
10	0734	21 00	- 0518	51 40	- 0276	-1·81	15770	7·12	·2264	2 33	·0948	3·70	750·7	13248	21·62	613	20480	9360	5383	1023	3206
11	0736	25 90	- 0748	56 05	-·0303	-7 92	16617		·2401		·1126		641·4	13845	27·20	509	22510	10862	5909	1233	3720

Table V. Unannealed Stalloy. Speed ·035(q.p.)

Nº	T	H_1	$-h_3$	ϕ_3	h_5	ϕ_5	B_1	θ	b_3	ψ_3	b_5	ψ_5	μ_0	B_{max}	H_{max}	μ	$\mathfrak{B}$	I	U	E	I-U-E
1	·0355	751	·0302	5°·67	0018	3°52	1044	24°·28	·0788	25°·34	·0189	32°85	1391	1034	·773	1347	1077	81·56	64 4	5·9	10 3
2	0354	1 047	·0285	7·43	·0047	6·16	2071	31·98	·0940	18·79	·0277	24 54	1977	1991	1·075	1852	2171	284 4	234	23·8	26·2
3	0357	1·498	·0270	9 92	·0039	25 15	4127	35·68	·1436	12·58	·0398	16·06	2754	3738	1·530	2444	4568	886·2	617	104 6	165 1
4	·0360	1 709	0385	12 00	·0025	23·49	4816	34·20	·1600	11·88	·0460	14·25	2819	4391	1 760	2499	5454	1115	785	147 7	182 3
5	0365	1 861	·0269	8·83	·0013	20·19	53 93	32·84	·1636	10·47	·0514	12 84	2898	4892	1 951	2509	6155	1326	915	185 9	225 0
6	0365	2·296	0282	7·52	·0039	13 51	6457	29·87	·1727	8·42	·0599	1145	2812	5732	2 424	2362	7522	1793	1232	277 8	283 2
7	0360	2 962	·0235	7·21	·0038	1 72	7568	26·87	·1842	7·88	·0675	9 27	2555	6627	3 240	2191	9015	2468	1624	4037	440 3

Table VI. Unannealed Stalloy. Speed ·021(q.p)

Nº	T	H	$-h_3$	ϕ_3	h_5	ϕ_5	B_1	θ	b_3	ψ_3	b_5	ψ_5	μ_0	B_{max}	H_{max}	μ	$\mathfrak{B}$	I	U	E	I-U-E
1	0209	·781	0286	7°30	·0008	8°10	1262	32°32	0795	25°·64	·0074	31°38	1616	1261	801	1542	1298	128 4	921	14 4	21·9
2	0209	1 072	0407	10·25	0005	11·79	2372	39 24	1063	20 60	·0193	26 31	2213	2325	1102	2067	2500	473 5	291·2	53·6	128·9
3	0208	1 500	·0269	10·78	·0024	12 38	3965	41 04	·1324	14·69	·0256	19 93	2642	3872	1·525	2486	4298	985·2	649 0	159·2	181·0
4	0212	1·699	·0249	15·07	·0038	13 55	4686	40·03	·1318	12 91	0306	17 87	2759	4363	1·726	2475	5090	1262	779·6	219·1	263·3
5	0215	1 897	0222	13 34	·0045	14·06	5231	37·60	1395	11·96	0362	15 94	2758	4816	1 928	2444	5749	1495	923 8	275·1	296·1
6	0216	2·289	·0222	11·39	0065	15·03	6319	34 50	·1530	9 96	·0424	13 90	2763	5726	2 398	2338	7084	2015	1231	415 4	368·6
7	0219	4 968	0474	5·99	·0134	18 81	9867	23 68	·1750	7·21	0610	10 68	1986	8626	5 050	1678	11537	4666	2500	1090	1076

Tables IV., V., VI., give the corresponding results for the unannealed ring.

In each set a space is left in the rows below which the influence of the higher harmonics begin to be noticeable. Generally the sign of these higher harmonics is negative in the magnetizing force, and in the induction always positive. S. P. Thompson's method of analysis was used for these more distorted waves and the inclusion of the higher harmonics considerably modified the total losses.

Above the space in the rows, the readings may be taken as belonging to approximately sinusoidal waves. In the graphs all the chief characteristics of the induction waves are plotted against the amplitude of their first harmonic (B_1).

The results of the statical experiments show several interesting features. The hysteresis constant has its maximum value about .0015 which is about the same as Epstein's value. On plotting it against the induction a smooth curve was obtained which rises from the origin to a maximum value at an induction of 3000 (the value of σ being .00122), it then decreases to a minimum at 4000, after which there is a steady rise which continues as far as the experiments go. This curve is similar in shape to that obtained when using ordinary iron.[1]

"Stalloy" needs careful handling especially in the unannealed state in order to obtain symmetrical results. When the magnetizing current is gradually increased and reversals are frequently the hysteresis loops are symmetrical and the Steinmetz coefficient when plotted against the maximum induction gives a smooth graph. But if, after working at high densities, an experiment is made with a small magnetizing force the loop will be found to be unsymmetrical and the corresponding value of σ will lie outside the previously obtained σ graph. This has also been drawn attention to by Wilson. In the unannealed state therefore "Stalloy" seems to be magnetically unstable so that the previous history of the material has a very marked effect upon its subsequent behaviour. The annealed "Stalloy" showed similar results but these were very little more noticeable than those obtained for ordinary iron.

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[1] T. R. Lyle. Loc. cit.

The other chief results of annealing are to increase the permeability and to lower the hysteresis loss. The values of the permeability μ did not rise to nearly the values obtained by other observers. For unannealed "Stalloy" the maximum is 2660 at an induction of about 4000 and in the annealed rises to 3500 at an induction of about 6000.

Table VII. Statical Results.

(a) Unannealed Stalloy.

No.	H_{max}	B_{max}	μ	U
1	·6366	743·2	1167	32·90
2	·9879	2301	2329	287·4
3	1·257	3338	2655	523·0
4	1·500	3987	2658	677·9
5	1·801	4734	2629	928·7
6	1·992	5161	2591	1057
7	3·189	6805	2134	1668
8	6·632	9404	1418	3061
9	11·747	11458	976·4	4172
10	19·497	12532	642·8	4609

(b) Annealed Stalloy.

No.	H_{max}	B_{max}	μ	U
1	·6411	684·4	1068	32·17
2	·9464	2262	2390	266·8
3	1·276	4152	3254	699·7
4	1·756	6074	3459	1318
5	1·977	6762	3420	1564
6	6·320	11645	1842	3966
7	16·035	13952	870	5600

The more important results of the experiments for alternating currents will be readily seen by reference to the accompanying figures while their more accurate details are given in Tables I. to VI.

In making comparisons between "Stalloy" and ordinary iron the results obtained by Professor Lyle for good samples of transformer iron have been assumed.

In Figs. 1, 2a, 2b, the more important characteristics of the induction waves which are set out in Tables I. and IV. are plotted against the amplitudes of the first harmonics of these waves.

The curves obtained for "Stalloy" are typical in general appearance of those obtained for iron and, although plotted here for only the lowest frequency, will be found similar in appearance for all the induction waves, provided the periods are constant throughout a series of experiments and are produced by currents of similar wave forms.

The characteristics μ_0 and θ fall in all cases to low values as the values of B_1 become small and probably vanish with B_1. The rise of θ in the region of low densities is steeper for annealed iron than for annealed "Stalloy," the appearance of the graph for iron being somewhat like that drawn here for the unannealed "Stalloy." There is this important difference, namely, that for iron, θ frequently rises to maximum of 52° whereas for "Stalloy" the maximum obtained for the same frequency was 47°.

The effect of annealing upon θ is to increase its magnitude for all inductions over about 2000. It will be noticed in the accompanying graph that the maximum value of θ increases on annealing from 33° to 38°. After attaining a maximum value for θ the graph assumes a steady downward gradient, which is practically constant for both annealed and unannealed samples. Along this gradient there is approximately a constant difference in value of θ of about 8° for all values of the above inductions. For ordinary working inductions therefore 8° may be taken as the increase effect produced upon θ by annealing.

A difference in the appearance of the permeability curve is to be noted. For iron this curve takes an almost parabolic form, having its axis vertical and its apex at an induction of about 10,000 the maximum value of μ_0 rising only a little above 3,000 generally.

Annealed "Stalloy" has a maximum permeability of 4140 which is attained at an induction of 6500, while the unannealed ring gives a maximum value of about 3100 at an induction of

4500. The μ_0 graph for "Stalloy" is therefore steeper for the smaller inductions before the maximum value is reached, after this the downward gradient is more gradual than for iron and at the same time more constant. In general, for a given induction μ_0 is considerably greater for "Stalloy" than for iron.

The effect of annealing is to increase the value of the characteristic very largely. The magnitude of this increase will be best seen in Fig. I, the corresponding curves for the other periods of alteration being very similar in appearance.

The total loss (I.) in the "Stalloy" shows a distinct improvement over that for iron. For all inductions and for all frequencies the total loss is found to be less for "Stalloy" than for ordinary iron of the same thickness. A very fair impression of the "Stalloy" total losses will be obtained by taking two-thirds of the corresponding values for ordinary iron at all inductions. It is also important to notice that these losses are greatly reduced by annealing. This reduction is not very appreciable for inductions below 5000, but above that there is a marked difference. It will be noticed however that the curves intersect where the induction is 15,500; for inductions above this the annealed losses increase very rapidly. In comparing these figures with those obtained for iron by Lyle it should be remembered that we have included the effects of the higher harmonics which in the unannealed ring were considerable. The conclusions arrived at for these total losses, namely that "Stalloy" is superior to iron in this respect and that annealing very considerably reduces such losses, although discussed for one speed only are fully borne out by the results for the other speeds as will be readily seen by plotting curves for the total loss from the other tables given.

Fig. 2a shows the effect of annealing upon the phase lag of of the third and fifth harmonics of the induction behind the first.

Both ψ_3 and ψ_5 fall rapidly from a maximum value for each as the value of B_1 is increased from zero, they then seem to reach small limiting values when B_1 is increased to high values. Here again as in the statical experiments the necessity of careful handling was proved imperative. We obtain further evidence of the instability of the unannealed "Stalloy," for in general the experimental variation from the graph is wider for it than for the annealed "Stalloy." In one series of experiments in which the readings were extended to an induction of about 20,000 the analysis showed that all the ψ's suddenly tended towards a zero value but as the higher harmonics were so pronounced and the wave form so distorted these results are not included in the tables or graphs. That these angles tend to zero value at the high inductions may be seen by plotting the readings for Table III.

Comparison with iron show that for extreme values, i.e., for very low and very high inductions the values of the ψ's are about the same. But between these limits the "Stalloy" gradient is less steep than that for iron especially for the higher frequencies, so that in general for a given induction ψ is greater for "Stalloy" than for iron. Annealing as can be seen in Fg. 2a has the effect of increasing ψ for all inductions, this increase being more marked in the higher frequencies.

In Fig. 2b are given the corresponding curves for b_3 and b_5. These curves apparently start from the origin, rise rapidly until $B_1 = 1000$ and then steadily and gradually increase. The shapes of the curves are similar to those obtained for iron, and the values obtained about the same, a very slight increase being noticeable. Annealing makes only a slight difference in these characteristics for the low frequency, for the curves intersect more than once, and what variation there is might almost be due to instability. On plotting the figures for the higher frequencies, however, we notice a gradual decrease as was the case for iron in the values of b_3 and b_5 as we increase the frequency, as well as a marked difference between the values for the unannealed and annealed "Stalloy," which amounts in the highest speed taken to about 10 per cent. of the latter.

From a practical point of view Fig. 3 is perhaps the most interesting. In this figure the values of the total, hysteresis, and eddy-current losses are given for the annealed ring. These curves show an almost proportional increase of I and E with increase of frequency. That this should be so for E is evident, but on examination we find that I is given approximately in terms of n and $\mathfrak{B}$ for values of induction up to 11,000 by the Steinmetz analogue proposed by Lyle for iron. Namely for the annealed ring.

$$I = (.00106 + .0000226n)\mathfrak{B}^{1.55}$$

and for the unannealed ring

$$I = (.00184 + .0000331n)\mathfrak{B}^{1.5.}$$

These forms agree fairly well with experiment except in a few isolated cases occurring chiefly in the unannealed sample. The value of the exponent for each case is remarkable, for it seldom falls below 1.57 for iron.

A fair average equation for transformer iron was found to be

$$I = (.00175 + .000027n)\mathfrak{B}^{1.57.}$$

The results for eddy-current losses found by us fully substantiate the claims made by the makers of "Stalloy." The value of the specific resistance was found slightly higher than that given by other experimenters but 50,000 may be taken as a fair working value. These discs, which are much thicker (.075 cm q.p.) than those usually used in iron work, show an eddy-current loss much less than that calculated for iron of only half the thickness, the value being about one quarter of the total loss. Seeing that for "Stalloy" I is itself less than for iron, the former must be considered admirably suitable for transformer work. The values of E increase rather considerably with increase of frequency the relative increase being greater than for I. This fact will be seen from Fig. 3 which gives all the losses to the same scale.

Perhaps the most remarkable results are those obtained for the hysteresis loss U. The values for the middle frequency (.035) only are plotted in the figures; but by examining the Tables I. and III. it will be found that the values for the other frequencies practically coincide with those from which the graph is plotted. Results for ordinary iron show an increase of U with frequency which although small is still much greater than the maximum variation for "Stalloy" which occurs between the frequencies .035 and .02. The values of U for frequencies .07 and .035 are practically identical. For "Stalloy" therefore U seems to be independent of the frequency and only about half the magnitude of that obtained for ordinary iron.

The values of the "kinetic hysteresis" I-U-E are given in the tables. On plotting, these results will be found to form smooth graphs which reveal an increase of magnitude with increase of frequency. Here again the values are less than those obtained for transformer iron. The values of U obtained by us are less than those obtained by Wilson, Winson and O'Dell, and others, but are practically identical with the results given by Barrett, Brown and Hadfield for a sample of silicon iron closely allied to "Stalloy" in composition.

Fig. 4, which shows the effect of variation of frequency upon the retardation and permeability for the annealed sample, is interesting in view of the results just referred to. In general the results show a similarity of variation to those obtained for iron, that is θ increases regularly with increase of frequency while μ_0 decreases. In both cases the maxima are reached at about the same induction, those for θ at an induction of 4500 and for μ_0 at an induction of about 6500.

One point is striking, namely, that the graphs for μ_0 for frequencies .035 and .02 intersect. Since there were a fair number of points taken and the results were very different in the two cases, this cannot be due to experimental error nor to any variation in the wave form of the magnetizing current, for the tables show this to be very constant. Corresponding to this deviation from the usual result will be noticed a distinct difference in the general appearance of the graphs for θ which is not existent in the graphs for iron. This correspondence is to be expected seeing that μ_0 and θ each depend on B_1 and ω as well as upon the wave form of H_1. Whatever deviation from the usual rule for iron there is, seems to have taken place in the middle frequency, so that for this particular frequency μ_0 is for inductions up 5000 less that one would expect. It may be possible that the previous high current densities used in the lower frequency had some after effect lasting until the maximum was reached, though precautions were taken to avoid this.

Summing up, therefore, generally, we may say that the chief results to be noticed are that—

(1) "Stalloy" cannot be used to advantage in the unannealed condition.

(2) In the annealed state the results obtained fully bear out the claims made by the makers, the permeability being very high and the losses small, particularly the eddy-current loss.

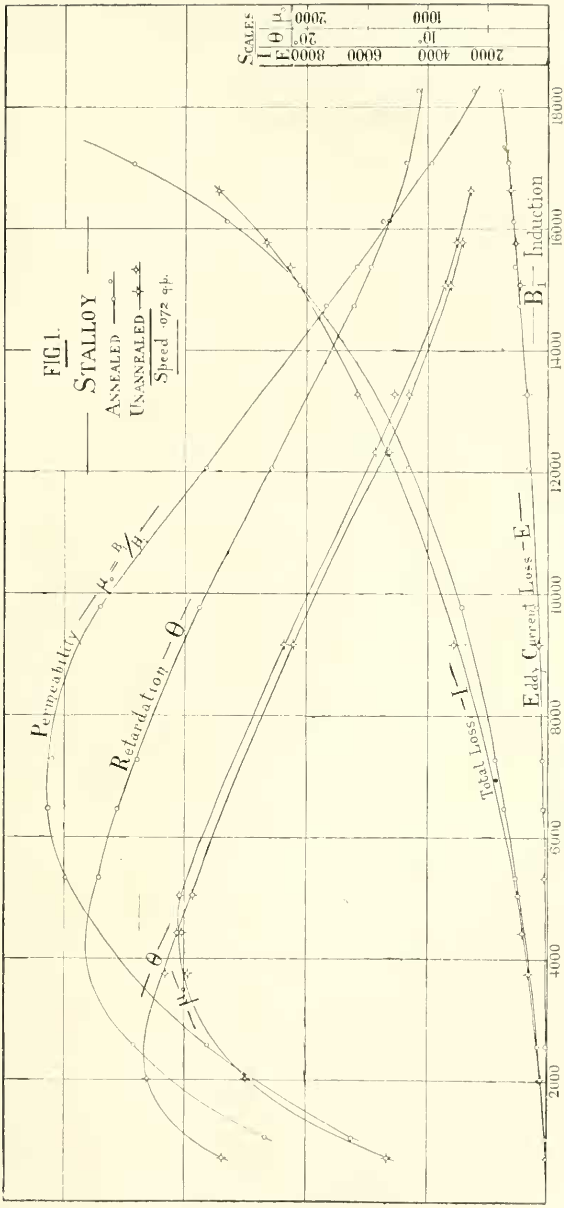
FIG.1.
STALLOY
ANNEALED
UNANNEALED
Speed ·072 q.p.
SCALES
I
θ
μ
E
2000
1000
20°
10°
8000
6000
4000
2000
Permeability — $\mu_\circ = B/H$ —
Retardation — θ —
— θ —
— μ —
Total Loss — I —
Eddy Current Loss — E —
— B_1 — Induction
2000
4000
6000
8000
10000
12000
14000
16000
18000